

## Q-SWITCHED HAFNIUM BISMUTH ERBIUM-DOPED FIBER LASER WITH BISMUTH (III) TELLURIDE BASED SATURABLE ABSORBER

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In this work, we fabricated the Bismuth (III) Telluride ( $\text{Bi}_2\text{Te}_3$ ) based saturable absorber (SA) by embedding the material into polyvinyl Alcohol (PVA) film. By incorporating the film inside laser cavity with a homemade Hafnium Bismuth Erbium-doped fiber (HBEDF) as a gain medium, a stable Q-switched fiber laser was generated to operate at 1532 nm region. The repetition rate of the laser was tunable from 41.1 to 61.0 kHz while corresponding pulse width shrinks from 9.46 to 5.48  $\mu\text{s}$  as the 980 nm pump power rises from 69 to 122 mW. The maximum pulse energy was 31.5 nJ. To the best of our knowledge, this is the first report on the Q-switched fiber laser using a relatively short length of HBEDF as the gain medium.

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### 1. Introduction

Passively Q-switched fiber lasers have been widely investigated owing to their potential applications in many areas including optical communications, remote sensing, medicine, and material processing [1-2]. Unlike the mode-locked fiber lasers which generally exhibit wide optical spectrum and ultrashort pulses, the Q-switched fiber lasers typically generate microsecond or nanosecond pulses with high pulse energy. Besides, passively Q-switched fiber lasers are attractive due to their cost, efficient operation, and easy implantation without much considering of dispersion and nonlinearity [3]. In recent years, a wide variety of SAs have been used in fiber lasers to obtain Q-switched laser pulses. Semiconductor saturable absorber mirrors (SESAMs), single-wall carbon nanotubes (SWCNTs) have been extensively studied and demonstrated in passively Q-switched fiber lasers [4-5]. SESAMs are mature SAs for their flexibility and robustness. However, the narrow operating bandwidth and high fabrication cost limit their application. For SWCNTs, the absorption wavelength is depend on the nanotube diameter, which means that they are not efficient. The emergence of two-dimensional materials effectively solve the problems above.

The discovery of graphene has given birth to the two-dimensional (2D) materials. New 2D materials, such as topological insulator (TIs), transition metal dichalcogenides (TMDs) and black phosphorus (BPs) have been reported to possess unique optoelectronic properties and Pauli

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blocking induced saturable absorption [6-10]. Among these excellent 2D materials, TIs have attracted much research interest due to their large modulation depth with efficient saturable absorption property [6-7]. Previously, Q-switched fiber lasers were demonstrated using Bismuth (III) Selenide ( $\text{Bi}_2\text{Se}_3$ ) SAs [11-12]. In this paper, we demonstrate a Q-switched fiber laser based on Bismuth (III) Telluride ( $\text{Bi}_2\text{Te}_3$ ) saturable absorber using a highly doped Hafnium Bismuth Erbium doped fiber as a gain medium. For this purpose, we prepare free-standing  $\text{Bi}_2\text{Te}_3$ -polymer composite SA film by implanting the powder of this material into a polyvinyl alcohol (PVA) host. The film is used in a fully fiber-integrated laser cavity for generating Q-switching pulses train. Gradually increasing the pump power, stable Q-switched pulses are obtained with the maximum output power and pulse energy of 1.86 mW and 0.031 nJ, respectively.

## 2. Preparation and optical characterization of SAs

Film saturable absorber is widely used in the Q-switched fiber lasers for their uniform quality and flexibility to integrate into the laser cavities. The  $\text{Bi}_2\text{Te}_3$  embedded in PVA film is prepared in the work. The commercially available few-layer  $\text{Bi}_2\text{Te}_3$  powder with molecular weight 800.76 g/mol was used to prepare the SA in our experiment. To prepare the host polymer, 1 g of polyvinyl Alcohol (PVA) (Sigma Aldrich) is dissolved in 120 ml de-ionized (DI) water with the aid of a magnetic stirrer at room temperature. Next, 14 mg of  $\text{Bi}_2\text{Te}_3$  powder was thoroughly mixed with 3 ml of the PVA solution using a magnetic stirrer for three hours. Then the  $\text{Bi}_2\text{Te}_3$ -PVA solution was then placed in ultrasonic bath for 10 minutes to make sure the powder fully binds with the PVA. After that, the  $\text{Bi}_2\text{Te}_3$  suspension was obtained and it was carefully poured onto petri dish to avoid trapping any air bubble. It was then left to dry at room temperature for 48 hours to form  $\text{Bi}_2\text{Te}_3$ -PVA composite film.

Fig. 1(a) shows the field emission scanning electron microscopy (FESEM) image of the fabricated  $\text{Bi}_2\text{Te}_3$  film. As shown in the figure, the  $\text{Bi}_2\text{Te}_3$  film has a high dense of micro-rods and micro-grains, which can be clearly viewed on the substrate surface and distributed randomly on the substrate surface. These micro-rods and micro-grains are in irregular shapes with an average size of 0.5 to 1.9  $\mu\text{m}$ . Fig. 1(b) illustrates the absorbance spectrum of the prepared  $\text{Bi}_2\text{Te}_3$ -PVA film in the range of 200 nm to 1100nm. The figure attests a constant absorbance which indicates that the film possesses a broadband resonance wavelength like graphene. Fig. 1(c) shows the Raman spectra of the fabricated film. It indicates only two peaks at  $\sim 62 \text{ cm}^{-1}$  and  $\sim 99 \text{ cm}^{-1}$  which belong to  $A_{1g}^1$  and  $E_g^2$  vibrational modes. This may be due to the low dispersion of the  $\text{Bi}_2\text{Te}_3$  nano powder in PVA. This could be improved by lengthening the stirring and sonification times.

The nonlinear optical response property for the  $\text{Bi}_2\text{Te}_3$  film was also investigated to confirm their saturable absorption by applying dual optical power meter techniques. The pulse input source used a mode-locked fiber laser, which has femtosecond output pulse with a 17 MHz repetition rate and a 900 fs pulse duration, which the output power is approximately 5 mW. Fig. 1(d) shows the transmission resulting characteristic, which was fitted using the following simple saturable absorption equation of

$$T(I) = 1 - \alpha_0 \exp\left(-I/I_{sat}\right) - \alpha_{ns}$$

where  $T(I)$ ,  $\alpha_0$ ,  $I$ ,  $I_{sat}$  and  $\alpha_{ns}$  stand for the transmission, modulation depth, input intensity, saturation intensity, and non-saturable absorption, respectively [17]. The modulation depth, non-saturable absorption and saturation intensity were measured to be approximately 30 %, 55 % and 40  $\text{MW}/\text{cm}^2$ , respectively as shown in Fig. 1(d).

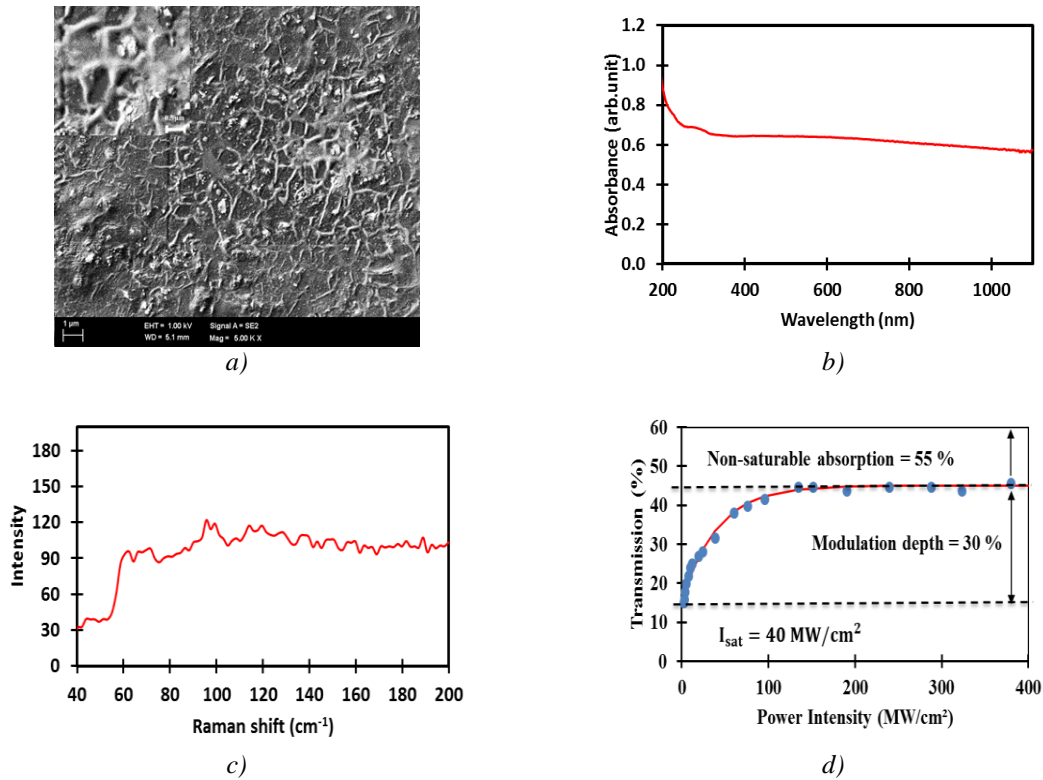


Fig. 1. Material characterization (a) FESEM image. Insert represents a high magnification of the image (b) Linear transmission (c) Raman spectrum (d) nonlinear absorption curve

### 3. Experimental setup

The schematic of the all-fiber Q-switched Erbium-doped fiber laser (EDFL) based on Bi<sub>2</sub>Te<sub>3</sub> PVA film SA is shown in Fig. 2. The gain medium is a 20 cm long of Hafnium Bismuth Erbium-doped fiber (HBEDF) with high absorption coefficient (100 dB/m at 980 nm). The fiber is estimated to have erbium ions concentration of 12500 wt ppm. The HBEDF is backward pumped by a 980 nm laser diode through a 980/1550 nm wavelength division multiplexer (WDM). A polarization independent isolator (PI-ISO) is used to prevent the bidirectional transmission in the laser cavity. A 10/90 coupler is used to output the laser emission for further using or monitoring. An Optical Spectrum Analyzer (OSA: Yokogawa, AQ6370B) and an oscilloscope (GWINSTEK: GDS-3352) with high speed photodetector are used to monitor the output spectrum and the pulse trains. 7.8 GHz Radio Frequency (RF) spectrum analyzer (Anritsu MS2683A) is used to investigate the repetition rate and stability of the Q-switched laser. The average output power of the pulse laser is measured by the power meter (ILX Lightwave OMM-6810B) coupled with its power head (ILX Lightwave OMH-6727B InGaAs). The Bi<sub>2</sub>Te<sub>3</sub> PVA film is cut into small pieces of 1×1 mm<sup>2</sup> and sandwiched between two fiber connectors inside the cavity for intra-cavity loss modulation. Index matching gel is applied at the connection to minimize parasitic reflections.

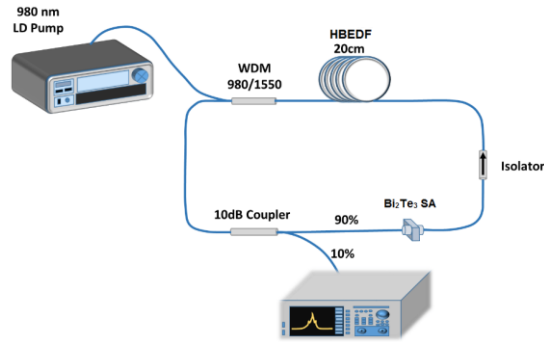


Fig. 2: Configuration of the Q-switched fiber laser with HBEDF as a gain medium and Bi<sub>2</sub>Te<sub>3</sub> PVA film as a SA.

#### 4. Results and discussion

The performance of the EDFL based on Bi<sub>2</sub>Te<sub>3</sub> PVA film SA was investigated by varying the power of the 980 nm pump. The continuous wave (CW) laser started as the power hit the threshold of 44 mW. Then, a self-starting and stable Q-switched operation was obtained when the pump power reached the threshold of 69 mW. Fig. 3 (a) shows the typically Q-switched pulse train at the threshold pump power. It indicates peak to peak separation of 24.3  $\mu$ s, which equivalent to 41.1 kHz repetition rate. The oscilloscope trace without pulse modulation also indicate the Q-switching operation is stable. The symmetrical Gaussian-shaped pulses in Fig. 3 (a) show the pulse width of 9.46  $\mu$ s. Fig. 3(b) shows the OSA spectrum from the laser, which indicates multiple peaks at 1532 nm region.

Fig. 3 (c) shows the measured pulse repetition rate and pulse width against the pump power. It is shown that the pulse repetition rate linearly increases, while the pulse width linearly decreases with the pump power. This matches well with the passive Q-switched theory based on SA. The pulse repetition rate of the Q-switched EDFL linearly increases from 41.1 to 61.0 kHz while the pulse width decreases from 9.46 to 5.48  $\mu$ s as the pump power rises from 69 to 122 mW. This is a typical trend due to the gain compression effect in the laser cavity. The pulse width is expected to drop further if the pump power can be increased more, as long as the damage threshold of the SA is not exceeded. Fig. 3(d) shows the measured average output power and the calculated pulse energy of the Q-switched EDFL as a function of pump power. As the nonlinear transmittance is influenced by the laser intensity, in this case, when the pump power is changed, the output laser pulse should also change. As seen in Fig. 3(d), both average output power and pulse energy linearly increases with the pump power. For instance, the output power increases from 1.06 to 1.86 mW with a slope efficiency of around 1.55% as the pump power increases in a range from 69 to 122 mW. The maximum output power of 1.86 mW is obtained at the maximum pump power of 122 mW, while the maximum pulse energy of 30.5 nJ is recorded at 122 mW.

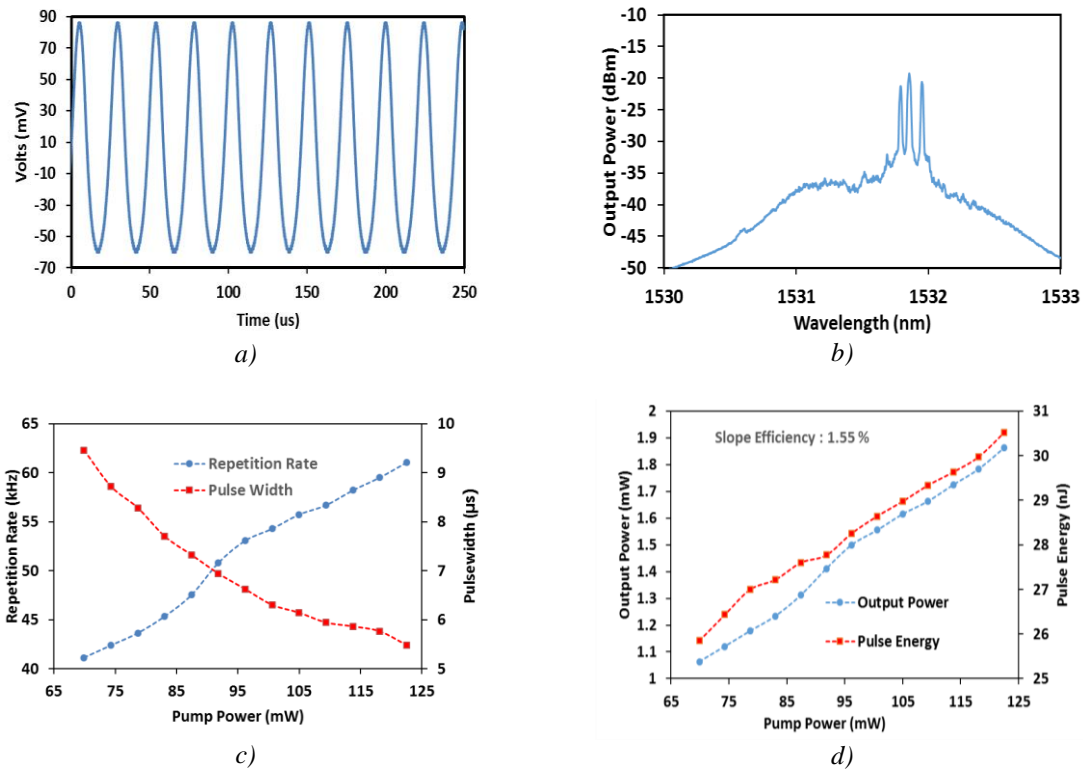


Fig. 3: Q-switching performances (a) typical pulse train (b) output spectrum (c) repetition rate and pulse width against pump power (d) average output power and single pulse energy against pump power

We measured the radio frequency (RF) output spectrum of the pulse trains as shown in Fig. 4 in a wide span of 450 kHz. We only observed the fundamental and the harmonic frequencies in the RF output spectrum, which further confirmed the stability of the Q-switching operation. The fundamental frequency was obtained at 61 kHz, which is in good agreement with the oscilloscope trace. The radio frequency spectrum analyzer has a minimum resolution bandwidth (RBW) of 100 Hz. The signal to noise ratio is 59 dB with the film SA. It is found that the  $\text{Bi}_2\text{Te}_3$  SA shows excellent Q-switching performance especially in single pulse energy and stability. To further improve the Q-switching performance or even obtain mode-locking operation, one could optimize the fabrication method of the  $\text{Bi}_2\text{Te}_3$ , reduce the cavity loss and increases the strength of the interaction between the SA and the laser pulses.

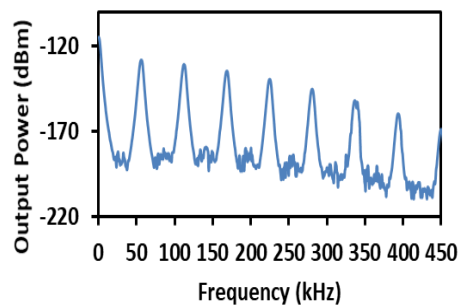


Fig. 4: RF spectrum at pump power of 122 mW

## 5. Conclusion

The Q-switched operations based on Bi<sub>2</sub>Te<sub>3</sub> PVA film based SA and HBEDF gain medium have been demonstrated in all-fiber EDFL. Self-starting and stable Q-switched pulse trains was obtained to operate at 1532 nm region. The pulses have a shortest pulse duration of 5.48  $\mu$ s, maximum pulse energy of 31.5 nJ. The pulse frequencies are tunable from 41.1 to 61.0 kHz as the pump power varies from the threshold pump power of 69 mW to 122 mW. The laser shows a good Q-switching performance in the 1.5  $\mu$ m wavelength region.

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